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Unidimensional heat transfer analysis of elephant grass and sugar cane bagasse slow pyrolysis in a fixed bed reactor

J.M. Mesa-Perez[a,*], L.A.B. Cortez[a], J.D. Rocha[b],
L.E. Brossard-Perez[c], E. Olivares-Gómez[b]

[a] *Faculdade de Engenharia Agrícola-FEAGRI/UNICAMP, Cidade Universitária "Zeferino Vaz", Barão Geraldo, CP 6011, 13084-971, Campinas SP, Brazil*
[b] *Núcleo Interdisciplinar de Planejamento Energético, NIPE/UNICAMP, Cidade Universitária "Zeferino Vaz", Barão Geraldo, CP 6086, 13084-971, Campinas SP, Brazil*
[c] *Faculdad de Ingenieria Química, Universidade de Oriente Sede Mella, ave, Las Américas sn, Ampliación de Terraza, Santiago de Cuba, CP 90 600, Cuba*

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Abstract

Elephant grass (*Pennicetum purpureum*) and sugar cane bagasse slow pyrolysis experiments was carried out in a fixed bed reactor. A 20-cm internal diameter and 12-cm-long reactor was used. Particulate biomass filled up the reactor volume. Biomass was loaded into the reactor and heated in the axial direction using an electrical resistance located at the reactor's bottom. In order to control the temperature variation during the biomass pyrolysis process, four thermocouples were installed inside of the reactor.

The remain residual mass was constant approximately after 73 min of heating; the running was stopped and remain carbonised; material was manually removed from the reactor. The residue formed three layer of biomass visually different described in detail here. Proximate analysis and higher heating value (HHV) tests were carried out to the material in each layer. Mass loss against time was recorded during experiments.

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* Corresponding author. Centro de Tecnologia da UNICAMP, Rua Bernardo Sayon, No. 100, Sala 207, 13083-866, Distrito de Barão Geraldo-Cidade Universitária "Zeferino Vaz", Brazil. Tel.: +55 19 3788 4996; fax: +55 19 3788 5030.

E-mail address: bioware@ct.unicamp.br (J.M. Mesa-Perez).

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The results indicated that the carbonisation ratio decreases in time because the carbon layer has low thermal conductivity and it does not permit proper heat transfer to the upper layer of biomass. It means that technology that avoids high-temperature gradients during the pyrolysis of bulk-dispersed biomass could avoid the problems described before.

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1. Introduction

Pyrolysis is a thermal decomposition which occur in the absence (fully or partially) of oxygen. Lower process temperature and longer vapor residence times favor the production of charcoal. Higher temperature and longer residence time increase the gas production, and moderate temperature and short vapor residence time are desired conditions for producing liquids [1].

Hu et al. [2] investigates the effects of coal particle size on pyrolysis in a fixed bed reactor. The results indicated that increasing particle size tends to decrease the gas production and diminish the heat exchange rate between cold and hot particles. The authors confirmed that heat transfer coefficient could decrease with increasing pyrolysis time and particle size. The decaying of the heat transfer coefficient with particle size results in the pronounced decrease of coal temperature for larger particles in a fixed bed.

Increased coal particle size results in a higher mass transfer resistance of volatile gas within the pores or bubbles of a coal particle and delays the time for the maximum release rate of volatile matter, hence lowering the gas amount of product [2]. Larfeldt et al. [3] and Jalan and Srivastava [4] obtained similar results.

Di Blasi [5] showed that when indirect heating is used, the conversion regime could be weak or intense. Weak conversion regime is associated with the presence of very large spatial gradients and with a significant activity of secondary reaction. Under intense conversion regime, the spatial gradients inside the particles are neglected, although the temperature profile may vary in time, depending on the external heat transfer rate. In this case, if the particle size is sufficiently small (smaller than 2 mm), intraparticle activity of secondary reactions is negligible even at high reaction temperatures.

This research describes the slow pyrolysis of a packed cylindrical sample of elephant grass (*Pennicetum purpureum*) and sugar cane bagasse in a fixed bed reactor of 20 cm of internal diameter and 12 cm of height.

In order to analyse the kinetic properties during biomass carbonisation, where the heat transfer phenomena are significant, some tests were carried out using both raw material. Temperature profiles along the reactor height during pyrolysis were measured by means of a computer-aided data acquisition system. Besides the mass loss of biomass, proximate analysis and higher heating values (HHV) of all products found in the layers were computed.

2. Experimental apparatus and procedure

A schematic diagram of the experimental setup is shown in Fig. 1. The parts are:

(1) pyrolysis reactor,
(2) technical scale,
(3) condensation system and
(4) the computer-aided data acquisition system.

The reactor has lateral thermocouples up to the center of the biomass particles and in the upper part where pyrolysis volatiles leave the reaction zone (5). At the bottom of the reactor are located two electrical resistances (1200 W each) to deliver a constant heat flux (6). The acquisition data system ("ScanLink", Bernant scanning thermometer, Model 692-0000, 1998) has 12 channel connected to thermocouples.

The following steps were followed experimentally:

Step 1 A total of 500 g of biomass (sugar cane bagasse or elephant grass) were loaded in the reactor. The sample had a volume of $37{,}699.10^{-4}$ m^3 and the same as the reactor internal volume. Table 1 shows physical properties of the biomass samples.
Step 2 After loading the biomass, the reactor was closed and placed on the scale. Vapor condensation system was connected and the heating system was turned on.
Step 3 The temperature profile for each run was recorded and plotted (Figs. 2 and 3).
Step 4 The mass loss was also measured during the experiments (Fig. 4). Heating was turned off when the mass loss stopped. Typical time to reach constant mass was 73 min approximately for both biomass samples. In all running, the top

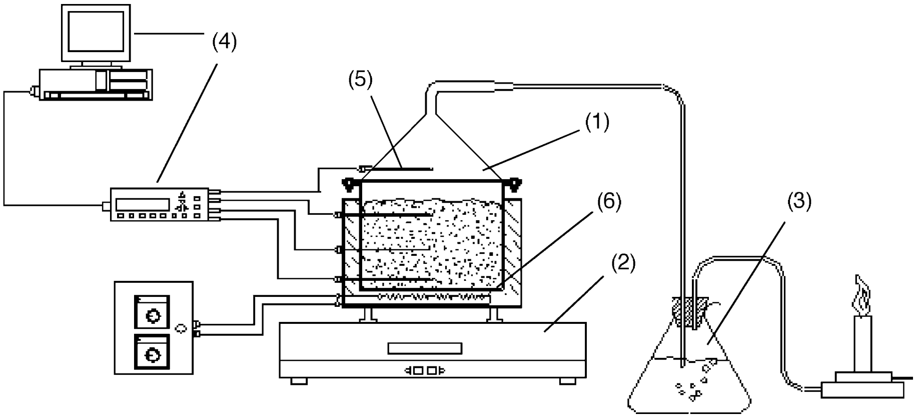

Fig. 1. Schematic diagram of the experimental setup.

Table 1
Physical properties for sugar cane bagasse and elephant grass (*in natura*)

Property	Sugar cane bagasse	Elephant grass
Fixed carbon content, %	11.4[a]	15[a]
Ash content, %	2.6±0.4	11±1
Moisture content, %	10±1	14±1
Volatile matter content, %	86±2	74±2
Higher heating value, MJ kg^{-1}	18.4±0.4	16.8±0.4
Skeletal density, kg m^{-3}	1440±20[b]	1468±7
Particle density, kg m^{-3}	535±15[b]	763±14
Bulk density inside the reactor, kg m^{-3}	132±2	132±2
Particle porosity	0.63±0.015	0.48±0.01
Particle size distribution, mm	$0.55<Dp<1.25$	$1.68<Dp<2.38$

[a] Calculated value.
[b] Rasul et al. [7].

temperature reached beyond 500 °C, in the nearest temperature point from the reactor bottom.

Step 5 After cooling the system to room temperature, residual biomass was unloaded. Three different layers were found (Fig. 5). Tables 2 and 3 present the temperature and the mass balance, respectively, for each layer.

Step 6 Each layer was carefully separated to avoid contamination, and proximate analysis and higher calorific value were done. Table 4 shows the analysis for both samples.

Step 7 Three experiments were carried out for each sample in order to quantify the experimental error. The mean temperature of each layer ($T_{m,n}$, where n is the layer number) was calculated using the following formulas, $T_{m,1}=(T_1+T_2)/2$, $T_{m,2}=(T_2+T_3)/2$, $T_{m,3}=(T_3+T_4)/2$, where, T_1, T_2, T_3 and T_4 are temperatures measured inside of the reactor as showed in Figs. 2 and 6. Figs. 3 and 7 shows the mean temperature of each layer ($T_{m,n}$) for both sugar cane bagasse and elephant grass, respectively.

3. Results and discussion

During the pyrolysis of biomass samples, the reaction zone was not extended uniformly throughout the entire particle. This fate is true because the heat and mass transfer processes have the same direction, i.e., from inner to outer zones. The heating rate depends on the size and the property of the biomass samples. In this case, heat conduction is the more important phenomenon and the thermal conductivity coefficient is the physical property that regulates the heat transfer velocity. Several researches show that during coal formation of many materials (wood, tire, etc.) [4,6], the thermal conductivity decreases and the resistance to a heat transfer increases.

The heat transfer between layers contributes to a temperature gradient as a function of the time, which is nonlinear, is shown in Figs. 2 and 6.

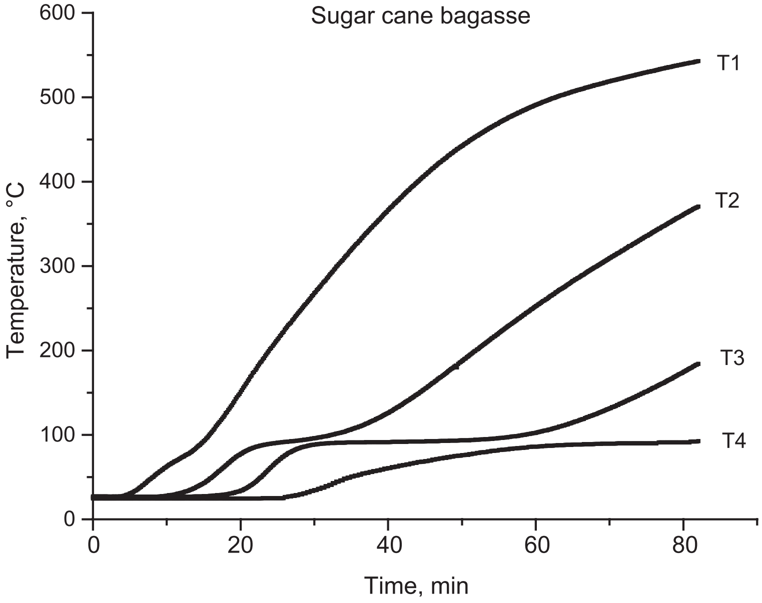

Fig. 2. Temperature profile for sugar cane bagasse.

Biomass moisture and volatile matter are a temperature function. Volatiles (water and organic vapors and some gases) from layer 1 (Fig. 5) have to pass through upper layers to leave the reactor. The heat exchange, involving hot volatiles from layer 1 and low temperature in upper layers, results in vapor condensation. The humidity in layer 3 is higher after the experiment due the condensation (Table 4).

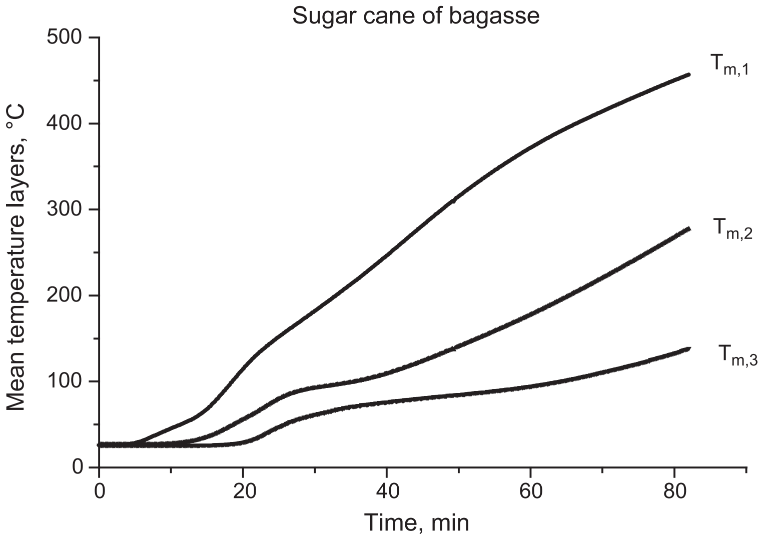

Fig. 3. Mean temperature of each layer for sugar cane bagasse versus time.

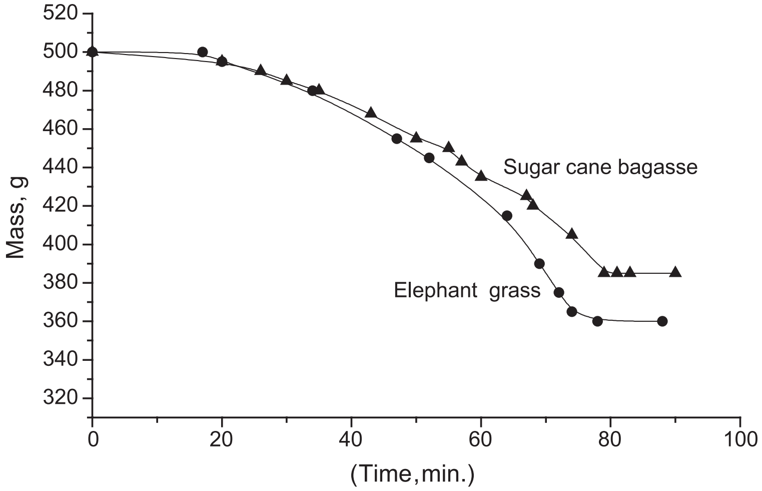

Fig. 4. Mass loss versus time for 500-g samples of sugar cane bagasse.

When layer 1 is completely devolatized, the total mass loss for all three layers remains constant. This happened approximately after 73 min: the average experiment time. It is necessary to increase the heat flow to reach the layer 2 and 3 pyrolysis. Such experiments are not presented in this communication.

Due t higher volatile matter present in sugar cane bagasse (Table 1), mass loss in layer 1 is relatively higher when compared to layer 1 for elephant grass experiments. Therefore, the vapor condensates in layers 2 and 3 are higher in the case of bagasse. As bagasse particles have higher porosity than grass (Table 1), bagasse is able to retain more condensates.

Table 2
Mean temperature of pyrolysis product layers at the end of thermo-conversion process

Biomass	Mean Temperature (°C)		
	Layer 1	Layer 2	Layer 3
Sugar cane bagasse	430±7	235±25	115±23
Elephant grass	430±7	235±10	115±6

Table 3
Mass of pyrolysis product layers at the end of thermo conversion process

Biomass	Mass in g		
	Layer 1	Layer 2	Layer 3
Sugar cane bagasse	109±4.5	102.5±1.5	186.5±15
Elephant grass	116.5±9.5	84±5	111±152

Table 4
Proximate analysis (in wt.%) and higher heating value (in MJ kg^{-1}) for pyrolysis product layers

Layer	$T_{m,n}$ (°C)	MC	FC[a]	VC	AC	HHV
Sugar cane bagasse						
In natura	30±2	10±1	11.4	86±2	2.6±0.3	18.4±0.4
3	115±9	22±1	10.5	88±2	1.5±0.4	19.4±0.7
2	235±40	8±1	25.4	72±2	2.6±0.6	20.7±1.12
1	430±22	6±1	61.9	33±4	6.1±0.3	24.2±1
Elephant grass						
In natura	30±2	14±1	15	74±2	11±1	16.8±0.4
3	115±7	16±1	12	78±2	10±1	17.7±0.4
2	235±11	8±1	15.9	70±2	14.1±2	18.2±0.4
1	430±44	8±1	47	33±3	20±2	18.9±0.4

[a] Calculated value.

Moisture content, fixed carbon, ash and volatile matter, as well as higher heating value (HHV), are presented in Figs. 8, 9 and 10, respectively, in function of mean temperature for each layer ($T_{m,n}$) and are obtained from regression models adjusted to data shown in Table 4.

The mathematical model for sugar cane bagasse is listed below:

Fixed carbon content

$$\mathrm{FC}(\%) = 0.0003T_{m,n}^2 - 0.0201T_{m,n} + 10,702 \quad (1)$$

Ash content

$$\mathrm{AC}(\%) = 5.0 \times 10^{-5}T_{m,n}^2 - 0.0136T_{m,n} + 2.7862 \quad (2)$$

Volatiles content

$$\mathrm{VC} = -4 \times 10^{-4}T_{m,n}^2 + 0.0307T_{m,n} + 86.63 \quad (3)$$

Higher heating value (MJ/kg^{-1})

$$\mathrm{HHV} = 145 \times 10^{-4}T_{m,n} + 17.74 \quad (4)$$

and the mathematical model for elephant grass is:

Fixed carbon content

$$\mathrm{FC}(\%) = -4 \times 10^{-4}T_{m,n}^2 - 0.0968T_{m,n} + 17.72 \quad (5)$$

Ash content

$$\mathrm{AC}(\%) = 5.0 \times 10^{-5}T_{m,n}^2 + 10^{-4}T_{m,n} + 10.43 \quad (6)$$

Volatile content

$$\mathrm{VC}(\%) = -4 \times 10^{-4}T_{m,n}^2 + 0.0967T_{m,n} + 71.852 \quad (7)$$

Higher heating value

$$\mathrm{HHV} = -1 \times 10^{-5}T_{m,n}^2 + 96 \times 10^{-4}T_{m,n} + 16.59 \quad (8)$$

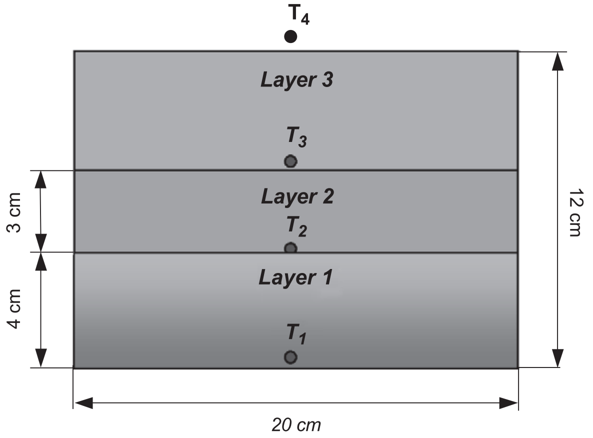

Fig. 5. Distribution of layers and location of temperature measurement points inside pyrolysis reactor.

These regression models have a determination coefficient, (R^2) of 98% at a 95% confidence level. The mathematical model was not developed for moisture content because of the insufficient amount of experimental points for model prediction fit.

Fixed carbon content increases gradually with time and exhibits a similar pattern for both types of biomass, as shown in Fig. 9.

Higher ash content in elephant grass determines a lower final fixed carbon compared to sugar cane bagasse. Ash content for both biomasses from room temperature to final

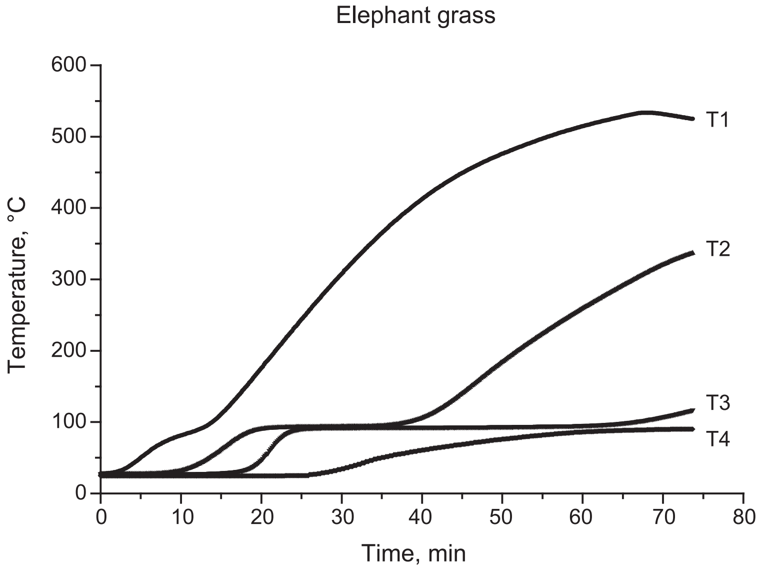

Fig. 6. Temperature profile for elephant grass.

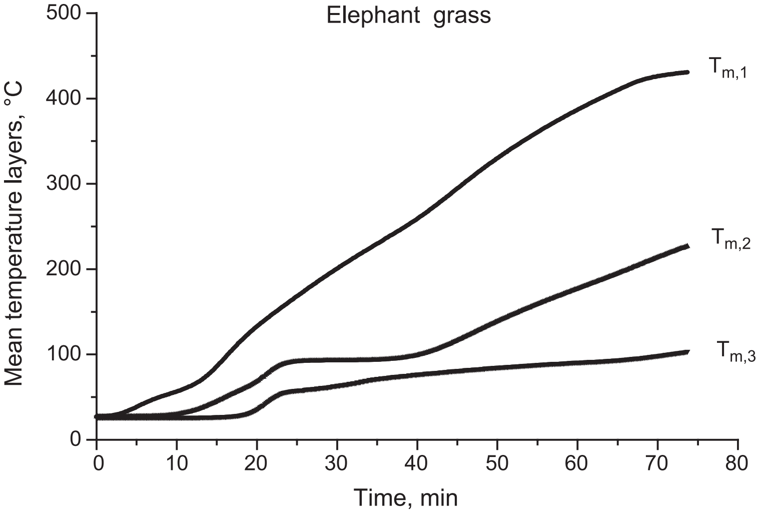

Fig. 7. Mean temperature of each layer for elephant grass versus time.

pyrolysis temperature is shown in Fig. 9. Biomass layers submitted to higher temperature regimes show also a higher ash content due to a progressively higher decomposition degree accompanied with volatile liberation.

On the contrary, volatile content decreases with a progressive temperature rising. Fig. 10 shows that although sugar cane bagasse has higher initial volatile content than elephant grass, it reaches the same final volatile content at the end of pyrolysis time and also shows a slightly higher devolatilization rate.

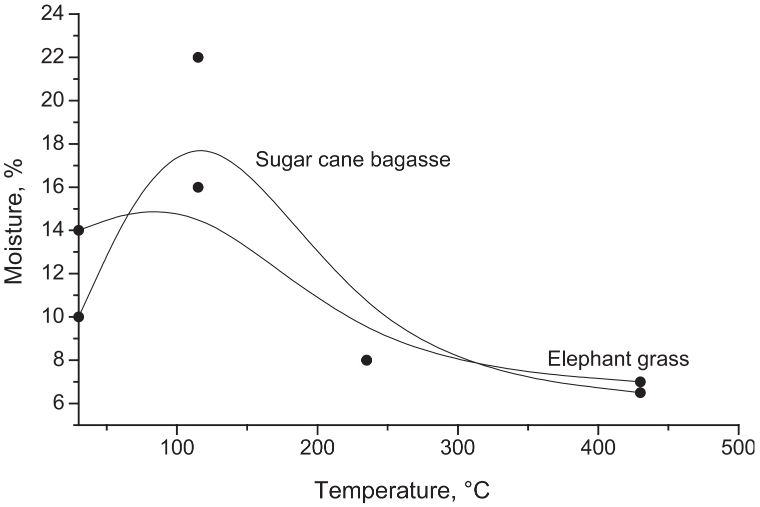

Fig. 8. Moisture content (wt.%) of each layer for sugar cane bagasse and elephant grass.

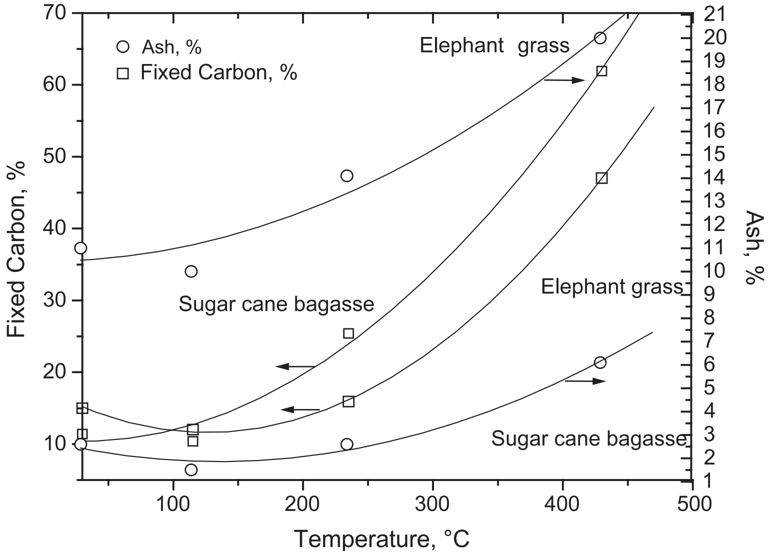

Fig. 9. Fixed Carbon content and ash (wt.%) of each layer for sugar cane bagasse and elephant grass.

Higher heating values (HHV) for pyrolysis product layers corresponding to sugar cane bagasse and elephant grass are shown in Fig. 10. It can be seen that for all registered temperature versus time, sugar cane bagasse product layers have a higher heating value than elephant grass. The lower ash content of this type of biomass explains this result.

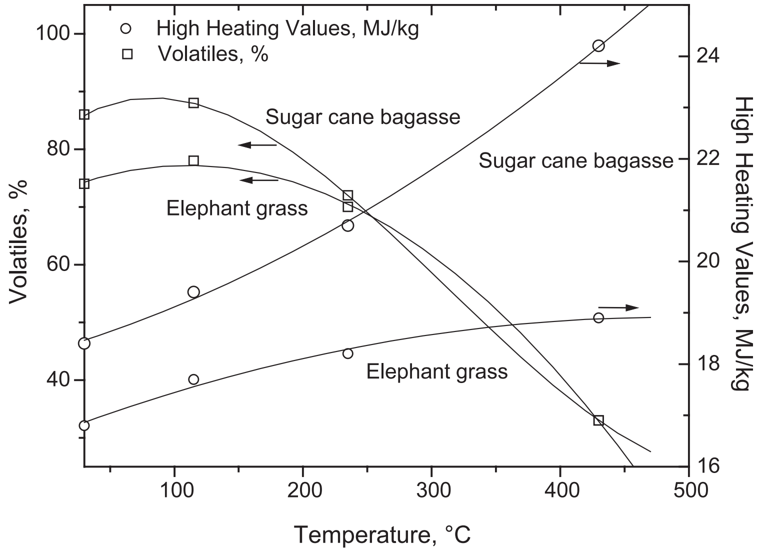

Fig. 10. Volatiles content (wt.%) and higher heating values (MJ kg^{-1}) of each layer for sugar cane bagasse and elephant grass.

4. Conclusions

Pyrolysis process is driving by heat and mass transfer, and pyrolysis reactions in a biomass particle. The basic process can be schematically described by three zones inside the particle such as char zone (outer zone), torrefied biomass zone (intermediate zone, this is the reaction zone) and in natura biomass zone (inner zone) Fig. 5.

Therefore, the temperature inside the particle increases, causing initially the removal of the moisture that is preset in the biomass particle, and subsequently, the torrefaction or prepyrolysis and pyrolysis reactions. As the char zone is becoming trickier, the thermal conductivity decreases and the resistance to a heat transfer increases. The temperature gradient appears and gradually increases and the inner zone is more difficult to heat.

Regression models obtained from experimental data describe the behavior of a series of characterizing properties (mass losses, moisture content, fixed carbon, ash, volatiles and higher heating value) of pyrolyzed big biomass particle along their sample's height.

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